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6. AUTHOR(S)
K. Banaszek, C. J. Foot, D. Lucas, D. N. Stacey, A. Steane, I. A. Walmsley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Oxford, Clarendon Laboratory, Parks Rd., Oxford, OX1 3PPU

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13. ABSTRACT (Maximum 200 words)

Work has been completed on the three projects supported by this grant. This Final Project Report summarizes the achievements of the project and then relationship to the project milestones highlights include deterministic entanglement between two trapped ions and the demonstration of the highest efficiency conditional single photon source to date.

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1. Ion Trap Project (DL, ANS, DS)

Year 1

The "pushing gate" that we intend to use to entangle ions was thoroughly studied theoretically (**milestone 1 complete**). We proposed a solution to a hidden weakness in the original proposal which led to extreme sensitivity to, for example, laser intensity noise. We demonstrate that fast gates of good fidelity are possible without ground-state cooling [1].

We implemented and quantitatively studied photo-ionization ion loading and optimized the loading process so that we could trap and laser-cool all the naturally-occurring isotopes of calcium (including the 0.004%-abundant ^{46}Ca). We can load single ions or small crystals "on demand", from a background vapour pressure 4-5 orders of magnitude lower than with electron bombardment, and with negligible drift in static electric fields between loads; this gives increased environmental stability for the ion-qubits and should reduce deposition on electrodes to a negligible level. Most importantly for the implementation of qubits, we can reliably load small, pure, crystals of the 0.14%-abundant $^{43}Ca^{+}$ ion (**milestone 2 complete**). The ability to do this without an enriched isotopic source was beyond our expectations and represents a significant experimental simplification. Isotope-selection of specific even isotopes (e.g. $^{48}Ca^{+}$) may also be useful for loading "refrigerator ions" to keep the $^{43}Ca^{+}$ qubit ions cold during gate operations [2].

We began the design process for our next-generation multiple trap (start of **milestone 3**), with studies of possible electrode structures. We designed and had built a high-power solid-state violet laser system in order to test its suitability for implementing the "pushing gate" (start of **milestone 4**).

David Lucas spent six months visiting the NIST Boulder Ion Storage group, where he took part in experiments which demonstrated a robust, high (97%) fidelity, two ion-qubit geometric phase gate [3].

Other work

We completed a detailed study of the threshold gate and memory failure rates necessary for fault-tolerant quantum computation [4]. More efficient and noise-tolerant syndrome extraction raised the threshold for fault-tolerance to the 10^{-3} level for certain computer architectures. This result represents an order of magnitude increase in tolerated memory noise compared with previous calculations, and was thus of major significance for the entire quantum computing community.

We proposed a new method for read-out of ground-state qubits in $^{40}Ca^{+}$, using a novel two-photon "bright-resonance" scheme [5]. With our existing apparatus we demonstrated both this method, and an improved method using electromagnetically-induced transparency (EIT) [6,7]. Experimental read-out efficiencies of up to 90% have subsequently been attained.

Year 2

Theoretical studies of the "pushing gate" were extended to the case of two ions in the same trap [8] (**extension of milestone 1**). The photo-ionization trap loading method was further optimized so that we can load pure crystals of $^{43}Ca^{+}$ of arbitrary size (**extension of milestone 2**).

We developed a general model for designing electrode structures for multiple trap systems, to optimize the design for maximum distance to electrode surfaces for given trap strength and separation [9]. We began a collaboration with Liverpool University to fabricate a multiple-trap system, and designs have been sent to them (**milestone 3 partially complete**). The system should be ready for testing during the coming year (**milestone 5**).

A high-power laser system for implementing the “pushing gate” was built and installed in our existing apparatus (**milestone 4 complete**). Pulse sequence electronics was designed and built, to allow more complex experimental sequences (e.g. Raman sideband cooling).

We achieved important goals on the way to implementing an entangling gate in our $^{40}Ca^+$ ground-level qubit: Rabi flopping, Ramsey fringes, spin-echo sequences, and sub-Doppler cooling (to $n<1$) using continuous Raman sideband cooling have all been demonstrated. These are essential ingredients for the achievement of milestone 6.

We used the “pushing laser” beams to implement single-ion phase gates and to drive Raman transitions of our $^{40}Ca^+$ qubit.

Year 3

The multiple-trap system was completed at Liverpool University (**milestone 3 complete**), installed in a new vacuum system and bake-tested (**milestone 5 partially complete**). Due to fabrication delays we have not yet attempted to load ions in this trap. A Raman laser system was built for coherent manipulation of $^{43}Ca^+$ hyperfine qubits (separated by 3.2GHz).

Three different sub-Doppler cooling methods were tested: continuous Raman sideband cooling, EIT cooling and pulsed Raman sideband cooling. The lowest single-ion temperatures attained were, in terms of the mean axial vibrational quantum number in a 0.8MHz trap, $<n>$=0.5, 0.2 and 0.01(2) respectively for the three methods. We measured the heating rate in both 0.5MHz and 0.8MHz traps to be consistent with 0.003(1) quanta/ms. This was lower than any published trap heating rate, even before taking into account the relatively weak trap strength, but is reasonable given the size of the trap (distance to nearest electrode 1.2mm). For two ions, in a 0.5MHz trap, we obtained simultaneous cooling of the centre-of-mass and stretch modes of motion to $<n>$=0.2(1) and 0.08(5) respectively. These temperatures were cold enough to attempt quantum logic operations.

As a diagnostic of the oscillatory “wobble” force necessary for a two-ion entangling gate (in the method of [3]), we applied the same force to a single ion. When applied to a spin superposition state, the result is entanglement of the ion spin and motional degrees of freedom. This is often described as a “Schrödinger Cat” state: the spin state is entangled with a quasi-classical motional state (a coherent state). The size of the “cat” is determined by the size (mean n) of the motional state and we have observed motional states as large as any ever produced ($<n>\sim 9$).

We then applied the same oscillatory force to a pair of ions in the 0.5MHz trap, to achieve deterministic entanglement of the two ions. The result is a controlled-phase gate, similar to that described in [3], which produces the entangled state (|00> – i|11>). Partial tomography of the entangled state indicated that it was produced with a fidelity of 75(5)% (**milestone 6 partially complete**). The entanglement was produced by a single laser pulse of 77_s duration. This result has not yet been extended to ions in different traps due to delays in commissioning the new multiple trap.

Other work
We sketched out the main features of a design for an ion-trap quantum computer capable of performing 10^9 logical operations on 300 logical qubits, based on reasonable extrapolations of current technology [10].

Publications

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[9] "Electrode Configurations for Fast Separation of Trapped Ions," J. P. Home, and A. M. Steane Arxiv pre-print, quant-ph/0411102. To be published in Quant.Inf.Comp.

[10] "How to build a 300 bit, 1 Gop quantum computer," A. M. Steane, Arxiv pre-print, quant-ph/0412165.

In preparation, based on work described in this report:

[11] "Continuous Raman sideband cooling of a single trapped ion", S.C.Webster *et al.*
[12] "Schroedinger Cat states of a single trapped ion outside the Lamb-Dicke regime", M.J.McDonnell *et al.*
[13] "Deterministic entanglement of trapped-ion spin-qubits", J.P.Home *et al.*

2. Photon Project (KB, IAW)

The research program in photonics has focused on the development of efficient photon sources and detectors for Linear Optics Quantum Computation (LOQC). In particular we have experimentally researched: the features of parametric downconversion (PDC) sources needed for LOQC; the possibilities for performing LOQC within the framework of integrated optics; and the construction and use of a photon number resolving detector.

The milestones for this project were:

1. Demonstrate close to unity singles to coincidence count ratio using quasi-phasematched waveguide PDC.
2. Use this source to implement event-ready Hong-Ou-Mandel (HOM) interferometer.
3. Design multi-waveguide Yurke-Stoler GHZ apparatus and begin to assemble triple coincidence counter.

Milestone 1 was completed, milestone 2 is in its final stages, and milestone 3 is still being investigated. The details of this progress are given in the following report.

Most of the work performed utilized PDC generated in a quasi-phasematched KTiOPO4 (KTP) waveguide using an ultrashort pump pulse. Initial experiments used Type I PDC, where the photon pairs created have the same polarization, making it difficult to probe the photons individually[i]. These results demonstrated many of the key advantages using a quasi-phasematched waveguide give over traditional bulk crystal sources. First, the technique of quasi-phasematching allows one to utilize larger nonlinear coefficients in some materials, thus leading to substantially higher production rates. Second, the waveguide structure provides a means to control precisely the spatial characteristics of generated photons, as the downconversion process is confined to well-defined transverse modes. Finally, in bulk crystals, the interaction length (and hence the PDC gain) is limited to the Rayleigh range of the focused pump beam; this problem is eliminated in a waveguided source. Also, waveguided sources of single photons are a first step towards LOQC with integrated optics. These were the initial steps towards achieving **Milestone 1**.

This work was extended to Type II PDC where the pairs of photons can easily be split by a polarization beamsplitter[ii]. Using this source we were able to observe a coincidence count to singles count ratio of 51% (corresponding to a conditional preparation efficiency of 85%) and extraordinarily high detection rates up to 8.5 * 10^5 *coincidences/(s mW)*, thus completing **Miletone 1**. This work is a key objective in the development of a bright source of polarization-entangled photons generated in quasi-phasematched waveguides. A new inequality that determines the degree to which the photon statistics of the source deviate from those of a classical source was derived and experimentally measured for this source[iii]. This inequality takes into account not only the photon statistics of the source, but also the affects of detection. The demonstration of nonclassical light generation via this route is a key goal toward achieving conditional entanglement, and thus an important step towards **Milestone 3**.

In the process of this work, we found it necessary to measure the the space-time mode structure of the single photons[iv]. Thus we invented and experimentally demonstrated a method for characterizing the spatial coherence of optical beams at extremely low light levels using avalanche photodiodes. This method will be essential in testing suitability of single-photon sources for the sort of multiphoton interference underlying LOQC primitives. In addition it provides a basis for exploring the entanglement of the continuous degree of freedom of a photon pair, which is significantly different than that of qubit systems.

The operation of LOQC requires the availability of entangled photon pairs on demand. **Milestone 2** is geared towards demonstrating the basic elements of interferometric protocols relevant to LOQC. We have introduced a novel scheme for generating maximal polarization entanglement in a conditionally deterministic manner that removed the inherent randomness in the production of entanglement[v] In the standard approach based on PDC, the presence of entanglement can be detected *a posteriori*, after all the signal photons have been destroyed. We have demonstrated that conditional detection performed on a higher-order term of the nonlinear interaction can yield unambiguous information about generating entanglement without destroying the photons. The scheme uses the three photon pair component of the PDC output and is optimal in the sense of the interaction order, as it has been shown previously that no lower order can produce heralded entanglement by means of conditional detection.

A further requirement for the successful preparation of entangled states, and indeed the logic gates of the KLM scheme of LOQC, is the ability to distinguish between zero, one, and two photons with high efficiency. We have designed[vi] and implemented[vii] a simple photon-number-resolving detector utilizing off-the-shelf fiber components and standard avalanche photodiodes that allows the discrimination of up to 8 input photons. A longer, joint article with the Johns Hopkins goup of J. D. Franson goes into further detail about the detectors operation[viii] We increased the efficiency of the detector to be greater than 30% by using multimode optical fiber. If the detection efficiency can be made greater than 50%, we shall be able to significantly improve the conditional interference experiments relevant to **milestone 3**. Using this detector we performed analyzed the photon number statistics of both a conditionally prepared single-photon and two-photon state[ix]. Also, using the photon statistics from the photon number resolving detector, we developed a novel, loss-tolerant method of characterizing nonclassical states of light[x]. The increased detector efficiency has allowed us to increase the fidelity of state preparation and we can now reliably generate a two-photon number state with over 90% probability. This detector will form a key enabling technology for **milestone 2**.

We have implemented technology to increase the rate of higher-order photon number states that are useful for cluster state generation and other tasks, such as entanglement distillation, that are needed for efficient quantum computation. In particular, we are currently working on getting six-fold photon coincidences at about 1 kHz. We are also beginning to examine conditional state preparation for entanglement generation in the non-Gaussian regime. Much effort was put into rebuilding and redesigning the laser system to make this work possible and current work focuses on utilizing the new laser in conjunction with the photon-number-resolving detector. This work constitutes important preliminary steps towards **milestone 3**, where pump energies must be high enough to conditionally prepare these GHZ states.

We have assessed theoretically the degree to which extraneous information in the states of photons from PDC affect the fidelity of Bell state measurements and Bell inequality tests[xi,xii]. This work forms the theoretical foundation for **milestone 2**. In the case where the interfering photons emanate from different nonlinear crystals, an interference visibility suitable for building a LOQC requires the photons be spectrally uncorrelated to a very high degree. We have illustrated the importance of this point by studying a practical implementation of the nonlinear sign shigft (NS) gate based on three PDC sources. By coupling the NS gate to a HOM Mach-Zehnder (HOM-MZ) interferometer, a sign shift in the NS gate translates into a change in the behavior at the output ports of the HOMI-MZ. Our calculations provide quantitative constraints on the source characteristics needed for these LOQC primitives, and we have shown that Type-II PDC sources are not compatible with these basic quantum logic operations. This places an extra constraint on the classes of sources that are needed for LOQC schemes.

Similarly, investigation of how spectral information in PDC can be engineered to give a heralded single-photon source that creates a *pure* single photon has been theoretically investigated[xiii]. Manipulation of the group velocity dispersion in the PDC process allows the creation of conditionally prepared photons that can interfere quantum mechanically (as is required in LOQC) without the need for spectral filtering. The final steps towards the experimental realization of this concept are currently being implemented in the lab, and once complete will indicate the completion of **milestone 2**.

Publications

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3. Atomic Project (CJF)

There were three main topics on which progress was made:

(a) Two-dimensional confinement of a Bose gas was achieved.

(b) Manipulation of atoms with the dipole force of a focused laser was achieved for samples of Bose-Einstein condensed atoms but not yet for individual atoms.

(c) A Feshbach resonance in rubidium-87 atoms was observed but it was found to be associated with very high losses making it unsuitable for use in controlling the interactions between atoms for in a collision gate (at least in our apparatus).

Combining the techniques developed in (a) and (b) we shall be able to confine neutral atoms in a plane (xy-plane) and manipulate then by means of the dipole force exerted by focused laser beams orthogonal to that plane (propagating along the z-axis). This experimental configuration that resembles optical tweezers method used to manipulate biological cells with a conventional microscope. In our case the atoms are in ultra-high vacuum at temperatures well-below 1 microkelvin (by laser cooling and evaporative cooling in a magnetic trap), so that they are in the lowest vibrational level of the dipole traps as required for future quantum information processing. Nevertheless the biological method and our work with atoms share some features, in particular state-of-the-art optical tweezers experiments use diffractive optical elements (e.g. spatial light modulators, SLM) to produce the desired intensity pattern and we have had considerable success in developing a system that can be used for ultracold atoms, for the which the manipulation needs to carried out on the millisecond timescale and there is no damping in the vacuum so intensity fluctuations. Further details are given in the following sections.

A. Experimental achievement of a two-dimensional Bose gas

We produced a Bose-Einstein condensate of Rb-87 atoms and 'squashed' the cloud flat along one axis by means of the repulsive dipole force from two sheets of laser light (with blue frequency detuning) positioned above and below the centre of the cloud. This made the oscillation frequency in the direction of tight confinement sufficiently high that the harmonic oscillator levels have an energy spacing less that the thermal energy and so only the ground level is occupied. There are numerous interesting physics experiments that can be carried out with this system but the main relevance for quantum computation is that is freezes out the motion in this direction so that we can create a two-dimensional array of atoms.

B. Manipulation of atoms with the dipole force of a focused laser

Working with members of the optics group in the Oxford Engineering department we have tested a liquid crystal phase array and set it up on the experiment apparatus. With this diffractive optical component we can diffract light into the patterns required for manipulation of the individual atoms (qubits) – a 'deformable' optical lattice. Such spatial light modulators (SLMs) can generate arbitrary and time-dependent patterns, allowing for dynamic and complex optical potentials. We have developed a method to program those devices in a way that produces sequences of diffraction patterns suitable to manipulate ultra-cold atoms (published work). To demonstrate the flexibility of the technique, we have generated a set of optical tweezers with an SLM, and used them to split a Bose-Einstein condensate and independently transport the separate parts of the atomic cloud along arbitrary paths in two dimensions (paper in preparation). A particular challenge in this work was to much sure that the light intensity changed slowly from one configuration to another, without dropping to zero at any time, since that would cause the cold atoms will be heated out the ground level, or even lost.

C. Observation of the Feshbach resonance

We built a magnetic system capable of producing a highly stabilized magnetic field and used it to observe a Feshbach resonance in at 1007 Gauss for the state F = 1, M = 1 of Rb-87 atoms. At the resonance it is predicted that one can convert the atoms into molecules by sweeping the magnetic field across the resonance. We saw and measured the loss of atoms due to the conversion, we could not observe molecules directly. We have also measured the atom loss due to 3-body recombination around the resonance. This data is interesting because it can potentially discriminate between competing theories of low temperature 3-body interactions. The theoretical group of the Atomic and Laser Physics laboratory of the University of Oxford, led by Prof. K. Burnett, is finishing the analysis. A paper is in preparation, in collaboration with this group.

Summary

Although the work on neutral atoms formed only a small part of this DARPA grant in Oxford, our link with this programme has been very useful, and experiments are continuing on the preparation of a two-dimensional array (e.g. 10x10 sites in the first instance) of ultra cold atoms in an optical potential with the ability to address and read out the quantum state of the atom at each individual site. When the quantum operations and manipulations can be carried out with sufficiently high fidelity this system will be useful for quantum information processing, however well before that level of control is attained such an array of atoms can be used for direct quantum simulation of condensed matter systems (as originally suggested by Feynman), e.g. two dimensional arrays of interacting spins. This system is a quantum analogue computer and by changing the optical potential (which is straightforward using the SLM) the device can by 'reprogrammed/restructured' to simulate a much range of configurations and interaction strengths between the qubits (spin-1/2 systems) at each site.

<u>Participation in conferences and other scientific events</u>

Poster presented at *Diffractive Optics 2003*, Oxford United Kingdom:
V. Boyer, C.M. Chandrashekar, C.J. Foot, Z.J. Laczik
« Dynamic optical trap generation using FLC SLMs for the manipulation of cold atoms »

Also attended the workshop *Diffractive Optics* of the same conference.

Poster presented at the International Conference on Atomic Physics (ICAP 2004, Rio, Brazil)

Publications

[1] V. Boyer, C.M. Chandrashekar, C.J. Foot, Z.J. Laczik, "Dynamic optical trap generation using FLC SLMs for the manipulation of cold atoms", *Journal of Modern Optics*, **51** 2235 (2004).
Note that Z. J. Laczik is from the Department of Engineering Science, University of Oxford.

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[3] G. Smirne, V. Boyer, D. Cassettari, R. M. Godun, C. J. Foot, K. Góral, and T. Köhler, "Resonance enhanced three-body recombination in cold gases of ^{87}RB: experiment versus theory", in preparation.